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High Resolution Millimeter Wave Inspecting of the Orbiter Acreage Heat Tiles of the Space Shuttle

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Abstract *– The physical cause of Space Shuttle Columbia's catastrophic failure was a breach in its thermal protection system, caused by a piece of External Tank insulating foam (SOFI) separating from the External Tank and striking the leading edge of the left wing of the Orbiter. Consequently, there is an urgent need for a rapid, robust and life-circle oriented nondestructive testing (NDT) technique capable of inspecting the SOFI as well as the Orbiter's protective heat tiles and its fuselage prior and subsequent to a launch. Microwave and millimeter wave NDT methods have shown great potential to achieve these goals using real focused reflectometer techniques and synthetic aperture focused techniques. This paper presents recent results of an investigation for the purpose of detecting anomalies such as debonds and corrosion in the structurally complex multi-sectioned protective heat tiles using a real focused 150 GHz (D-band) reflectometer and wide-band millimeter wave holography at 18-26.5 GHz (K-band) and 33-50 GHz (Q-band). The results of these investigations clearly show the utility of millimeter wave NDT methods for detecting such anomalies. Both methods provide a significant amount of information about the nature of an anomaly including size and location.*

Keywords *– millimeter waves, high resolution, nondestructive inspecting, space shuttle, heat tiles*

I. INTRODUCTION

Defects such as debonds, delaminations, and impact damage in the thermal protection system can adversely impact the safety considerations for the Space Shuttle and its crew. The physical cause of Space Shuttle Columbia's catastrophic failure was a breach in its thermal protection system, caused by a piece of External Tank insulating foam separating from the External Tank and striking the leading edge of the left wing of the Orbiter [1]. There is an urgent need for a rapid, robust and life-cycle oriented nondestructive testing (NDT) technique capable of inspecting the External Tank insulating foam as well as the Orbiter's protective (acreage) heat tiles and its fuselage prior and subsequent to a launch. Such a comprehensive inspection technique would enable NASA to perform life-cycle inspection on critical components of the Orbiter and its supporting hardware. Consequently, NASA Marshall Space Flight Center initiated an investigation into several potentially viable NDT techniques for this purpose. One of these techniques, microwave and millimeter wave NDT methods, has shown great potential to achieve these goals [2-5]. These methods have been successfully used to produce images of the interior of various complex, thick and thin External Tank insulating foam structures for real focused reflectometer at operating frequency from 50-100 GHz [2-3] and for synthetic aperture techniques at Ku-band (12-18 GHz) and K-band (18-26.5 GHz) [4-5]. Preliminary results of inspecting heat tile specimens show that increasing the resolution of the measurement system is an important issue [3]. This paper presents recent results of an investigation for the purpose of detecting anomalies such as debonds and corrosion in metal substrate in complex multi-sectioned protective heat tile specimens using a real focused 150 GHz (D-band) reflectometer and wide-band millimeter wave holography at 18-26.5 GHz (K-band) and 33-50 GHz (Q-band).

II. DESCRIPTION OF THE SPECIMENS AND MEASUREMENT APPROACHES

A. Heat Tile Specimens

The acreage heat tiles are multi-layered structures composed of a variety of ceramic-like materials capable of insulating the fuselage of the Space Shuttle Orbiter from the extreme heat encountered during its re-entry into the atmosphere. The heat tiles are in the family of low loss dielectric materials but with higher relative permittivity than spray on foam insulation (SOFI). Two different acreage heat tile specimens were used in the course of this investigation: (a) debond and repair specimen and (b) surface defect and corrosion specimen.

The first of two acreage heat tile specimens used in this investigation is shown in Figure 1a. It was composed of nine individual square tiles with an approximate area of 150 mm by 150 mm with varying thicknesses in the range of 15 mm to 30 mm (even within a given tile) and three rectangular tiles with an approximate area of 75 mm by 150 mm. Aluminum substrate of this specimen had two square and one rectangular thin pockets. Various anomalies representing thin debonds of different shapes and poor bonds between the tiles and substrate as well as circular repair regions inside the tiles were embedded in this specimen.

(a) (b)

Figure 1. Picture of (a) first heat tile specimen with debonds and repairs and (b) second heat tile specimen with surface defect and corrosion.

The second acreage heat tile specimen used in this investigation is shown in Figure 1b. It was composed of seventeen diagonally arranged individual square tiles with identical height and aggregate larger approximate area than the first specimen. Each tile measured approximately 150 by 150 mm. Here, one tile covered many small induced aluminum oxide corrosion pits in the aluminum substrate with various depth and size, six other tiles represented various shapes of surface defects as seen in white, and the remaining tiles represented no defect and no corrosion.

B. Measurement Approaches

In this investigation, two high-resolution inspection approaches were used namely; a real focused millimeter wave approach using lens antennas and wide-band millimeter wave holography using low-gain (synthetic-focused) antennas. For both approaches the heat tile specimens were placed on a 2D automated scanning table. The reflectometers were held at a fixed position above the specimens while the table moved the specimen underneath the reflectometers.

The real focused millimeter wave reflectometer systems that have been used at V-band (50-57 GHz), W-band (75-110 GHz) and D-band (110-170 GHz) incorporated lens antennas so that the radiating beam could be focused to a small footprint. The systems operating at 100 GHz and 150 GHz have been very successful in detecting the various anomalies mentioned above. However, the 150 GHz reflectometer system provided for a smaller footprint of approximately 2 mm in diameter. In addition, given the nature of the heat tile it is expected that at frequencies much above 150 GHz the signal will experience significant reflection from the surface of the tiles and scattering within the specimen. At this frequency, 2D raster scanned images of the specimens were produced at different standoff distances (e.g., the distance between the lens and the surface of a specimen). A DC voltage, proportional to the reflected signal power from the specimen under test was then measured at each location and recorded in a matrix corresponding to the scanning area. Subsequently, the measured voltages in this matrix were normalized (with respect to the highest voltage value) and a gray-scale or color image of the specimen was produced.

Wide-band millimeter wave holography is capable of producing relatively high-resolution 2D and 3D images of the interior of the specimen without necessitating a physically large antenna to produce a small illumination size [6]. Instead, a large antenna is synthesized through the movement of a small antenna rendering a synthetically produced antenna array (i.e., antenna with a narrow beam), which results in measurements with high spatial resolution. The measurement time for one scan of the specimen by this method is comparable to measuring with the lens antenna and subsequent processing and rendering time is less than one minute. The advantage of this method is that 3D images of the specimen (or 2D images of the specimen at different depths) can be generated from the data obtained in one scan. For the purpose of inspecting the heat tile specimens, measurements of the complex reflection coefficient were conducted in two different configurations using an Agilent E8361A Network Analyzer. First, the measurements were taken every 4 mm with 101 sampled frequency points with a K-band (18-26.5 GHz) open-ended rectangular waveguide probe. Second, measurements were taken every 2 mm with 201 sampled frequency points with a Q-band (33-50 GHz) open-ended rectangular waveguide probe.

III. RESULTS

Figure 2a shows the millimeter wave image of the heat tile specimen composed of twelve individual tiles obtained using the 150 GHz reflectometer with a lens antenna while Figures 2b and 2c show the wide-band holography images at 18-26.5 GHz and at 33-50 GHz, respectively. It must be noted that the image shown in Figure 2a is the raw image and no signal/image processing was applied to it. This is significant since it shows the effectiveness of this millimeter wave NDT method for producing rapid and

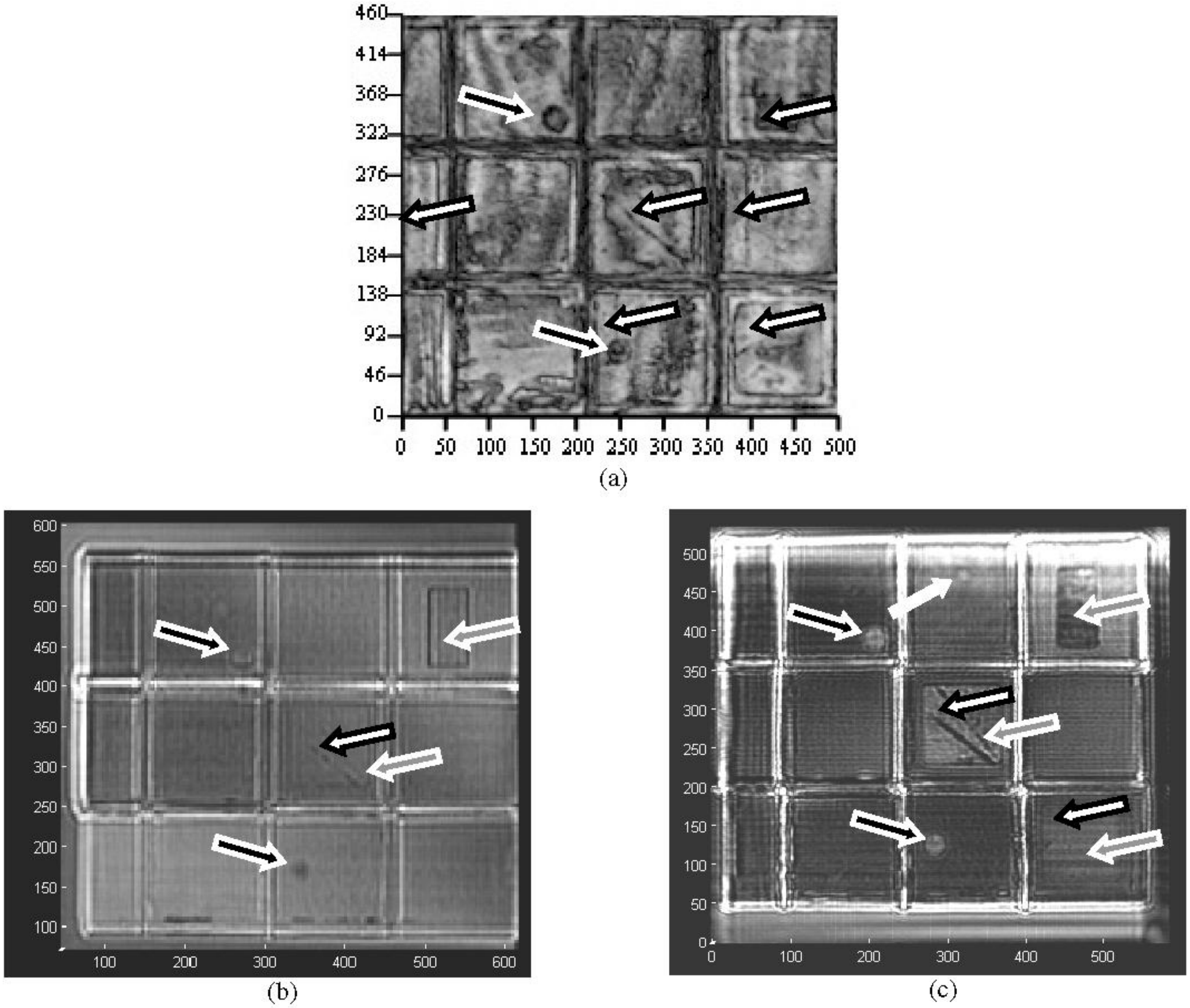

Figure 2. Millimeter wave images of the first heat tile specimen obtained using (a) 150 GHz reflectometer with a lens antenna and wide-band holography at (b) 18-26.5 GHz and (c) at 33-50 GHz (dimensions in mm).

informative images about the interior of the heat tile specimen as opposed to its surface. The debonds of different shapes (marked by white-on-black arrows) under six of the tiles as well as the two circular repair regions (marked by black-on-white arrows) are clearly evident. The image shown in Figure 2a also shows a number of unknown indications whose shape most likely indicates them to be from poor bonds and non-uniformities in the adhesive layer between the tiles and the substrate.

Figure 2b and 2c show holograms viewed from above using K-band (18-26.5 GHz) and Q-band (33-50 GHz), respectively. This view/image of the specimen demonstrates very clearly indications of some debonds (marked by white-on-black arrows), repair regions (marked by black-on-white arrows) as well as the pockets in the substrate (marked by grey-on-white arrows) with sharp boundaries. The image of the middle square tile possessing diagonal debond clearly shows the debond and its respective spatial extents. Three indications of the pockets in the substrate are visible more clearly than those in the image obtained with the 150 GHz reflectometer. Additionally, the image at Q-band provides higher resolution, clearer results, and more indications than the image at K-band, as expected. The unknown anomaly (marked by white arrow) was also clearly detected, as shown in Figure 2c. The specimen could not be dissected to verify the anomaly since the same specimen had to be preserved for other inspection methods not utilizing millimeter wave technology.

Figure 3 shows a slice of the hologram from the specimen shown in Figure 1b corresponding to the substrate viewed from above using Q-band (33-50 GHz) containing the region of interest. Surface defects in the heat tile are readily apparent. More interestingly, the tile covering an unknown number of corrosion pits in the far lower left corner of the image cannot mask the corrosion at millimeter wave frequencies, as shown in Figure 3. Eight of these indications were identified in the hologram. This sample also could not be dissected for interrogation since other additional inspection methods would be performed on the same specimen. It is important to note that this inspection method was simultaneously sensitive to surface as well as interior indications.

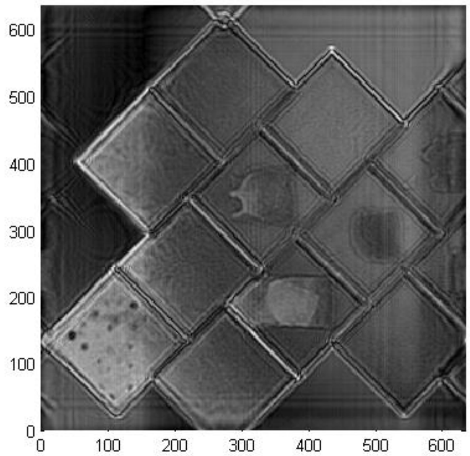

Figure 3. Millimeter wave image of corrosion specimen using wide-band holography at 33-50 GHz (dimensions in mm).

IV. SUMMARY

Anomalies such as debonds and poor bonds between the heat tiles and substrate in the thermal protective system of the orbiter can significantly reduce its insulating effectiveness. Additionally, these anomalies may cause complete separation of the heat tiles from the fuselage exposing it to extreme heat. Millimeter wave NDT methods have shown a great potential for detecting anomalies in heat tiles specimens similar to those used in the space shuttle. Increasing resolution of measurement systems and providing 3D imaginary of heat tiles in order to evaluate comprehensively the state of health of the tiles are important issues. The results of these investigations demonstrate that the real focused 150 GHz reflectometer produces high resolution images of the specimen without the need for image processing algorithms. The wide-band millimeter wave holography at 18-26.5 GHz and 33-50 GHz provide high-resolution images of the specimen at different depths using data of one scan and a relatively simple processing algorithm. Additionally, the use of wide-band millimeter wave holography at 33-50 GHz provides high resolution images useful for the detection of corrosion indications under acreage heat tile. Both methods provide a significant amount of information about the nature of an anomaly (e.g., size, location, etc.).

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